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Material Properties of Cold-Rolled Thin-Walled Steel Plates at Elevated Temperatures

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Material properties of cold-rolled thin-walled steel plates at elevated temperatures

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Abstract

It is highly important to clarify the high temperature mechanical properties in the design of cold-formed steel structures under fire condition due to the unique deterioration feature in material properties under fire environment and associated reduction to the mechanical performance of members. This paper presents the material properties of coupons cut from raw cold-rolled thin-walled steel plates at elevated temperatures. A set of high temperature extensometer with a range of 12.5mm relative to 50mm gauge was employed in the experiments, which could collect more displacement data between the gauge scope before the coupon fail. The coupons were extracted from original cold-rolled plates of GR340, GR410 and G550 steels with thickness of 1.0mm and 1.2mm, and a total of 50 tensile tests were carried out by steady state test method for temperatures ranged from 20 to 700°C. Based on the tests, material properties including the yield strengths, ultimate strengths, the elasticity modulus and the stress-strain curve were obtained. Meanwhile, the ductility of cold-formed steel plates were discussed. Finally, the temperature-dependent retention factors of all the material properties were compared to those provided by design codes and former researchers.

Key words

cold-rolled steel plate, material properties, elevated temperatures, temperature-dependent retention factor

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Introduction

As the main components in steel structural buildings, cold-formed steel (CFS) members are manufactured from cold bent sheet steel, approximately from 0.5mm to 25.0mm thick. The most common members are channels (tracks) and lipped channels (studs and joists). Cold-formed steel studs and tracks are used extensively in low-rise residential, factories and office buildings as the frame for interior partition walls, exterior curtain walls, and more recently as the complete load-bearing system. Consequently, fire issues gradually reveal in facilitating process of these type of structures. However, there are limited investigations about fire-resistance on cold-formed steel sections, and no related provisions in standard design codes around world.

Understanding the temperature dependence of CFS material properties is an essential step towards the development of accurate and effective fire design methods for CFS structural engineering application. As temperature increasing, steel members lose strength and stiffness, retaining only part of their ambient temperature capacity. The considerably material degradation at elevated temperatures, which is commonly considered via the use of retention factors, is the major cause of the above-mentioned failure. Generally, retention factors for the mechanical properties of CFS at elevated temperatures would be provided by design codes and standards, but the current provisions on temperature related retention ratios of CFS are based on the investigation upon hot-rolled steels (AISC 2010, AS 1998, BSI 1990, CEN 2005). However, CFS members develop faster heating rates for having higher thermal conductivity ratio and thinner sections than hot-rolled steel members. Then, the strength reduction of CFS at elevated temperatures may be higher than that of hot-rolled steels due the chemical composition and cold-rolling process effects. Moreover, when heated up, CFS are also likely to lose the strength gained through cold-working in the forming process (Lee et al. 2003). Therefore, retention factors obtained from hot-rolled steel tests may overestimate the capacity of CFS mechanical properties under fire.

In recent times, some studies have been under taken for mechanical properties of CFS at elevated temperatures (Outinen 1999, Lee et al. 2003, Chen and Young 2007, Ranawaka and Mahendran 2009, Kankanamge Mahendran 2011, Chen and Ye 2012, Ye and Chen 2013). In general, tested specimens range from 0.50 mm to 3.00 mm thick, with yield strengths from 250 MPa to 550 MPa at ambient temperature. Retention factors differ among research results and the proposed prediction equations vary as well. Differences are mainly attributed to the test method, strain rate, heating rate, material grade, material thickness, the criteria used to determine the yield strength and elastic modulus, and the fitting method used to generate constitutive equations. Previously, the specimens in most of research efforts were cut from CFS members which contain the cold-formed effect, and a 25mm gauge with small displacement range was commonly adopted leading to limited strain collection during tests.

This paper presents a detailed experimental investigation of the material properties of three types of sheets cut from original CFS coils. The steady state methods are considered and a wide-range high temperature extensometer system was applied. Finally, the reduction factors of the mechanical properties are compared with those in current design codes and other available literatures.

Experimental study

Test method

Different methods may be used to evaluate the mechanical properties of building materials under fire. The most popular method currently used to investigate the mechanical behavior of steel at elevated temperatures is the steady-state test in which the specimen is heated up to a target temperature and then, when the temperature is stable and uniform in the plate, gradually subjected to a tensile load until fracture happens. Another common method is the transient-state test in which the specimen is applied a static load and then heated up evenly until failure criterions are met. Most of researchers employ steady-state test techniques since it is able to obtain stress-strain curves directly, avoids fluctuant temperature environment, eliminates the influence of creep deformation, and generally saves resources. Therefore, steady-state test method was adopted in this experimental investigation.

Test specimens

The coupons were cut from original cold-rolled plates of GR340 and GR410 steels with nominal thickness of 1.0mm, and G550 steels with nominal thickness of 1.2mm. All of the test specimens were cut in the transverse direction of the cold-rolled steel plates by a wire cutting machine. The dimension of the test specimens was determined by ISO 6892-2, as presented in Figure 1. The specimens were flat with small lug for fixing extensometer system and two holes for pinned connections. The average thickness of zinc coating of specimens was 0.03mm provided by mill sheet. The metal thickness and gage width of the specimens were measured at three points within gauge lengths by using a micrometer before testing. The base metal thickness and real gage width were used in the calculations of the initial cross sectional area.

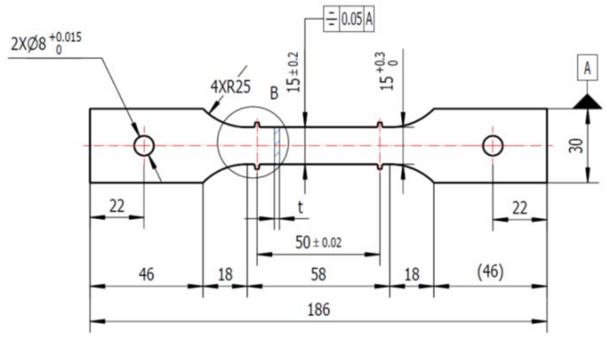

Figure 1. Dimension of test coupons

Test devices and procedure

The tests were conducted in the Fire Safety of Engineering Structures Testing Division of State Laboratory for Disaster Reduction in Civil Engineering in Tongji University. The test system is shown in Figure 2, which contains a testing machine with a capacity of 100kN, a high temperature furnace with a maximum temperature of 1200°C, a set of linear displacement grating with high temperature resistance extension rods, three thermal couples binding in a range of 150mm, and controlling computers. Figure 3 and Figure 4 present details of the testing devices.

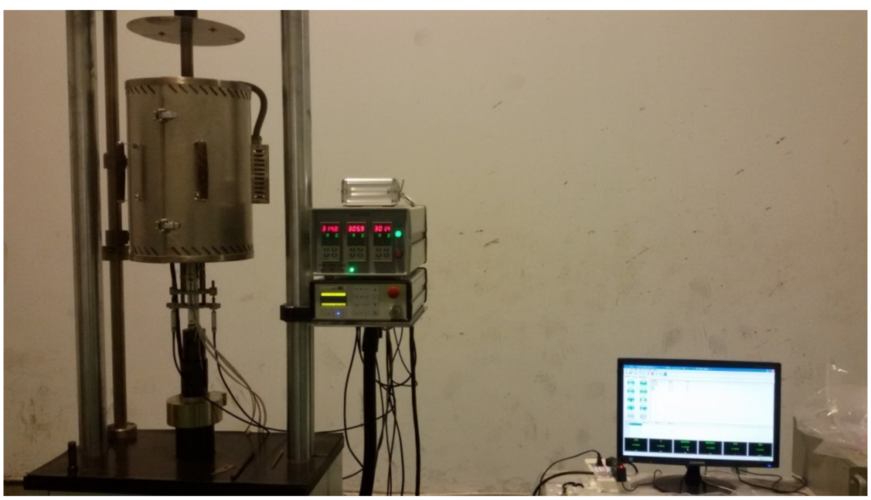
Figure 2. Testing system

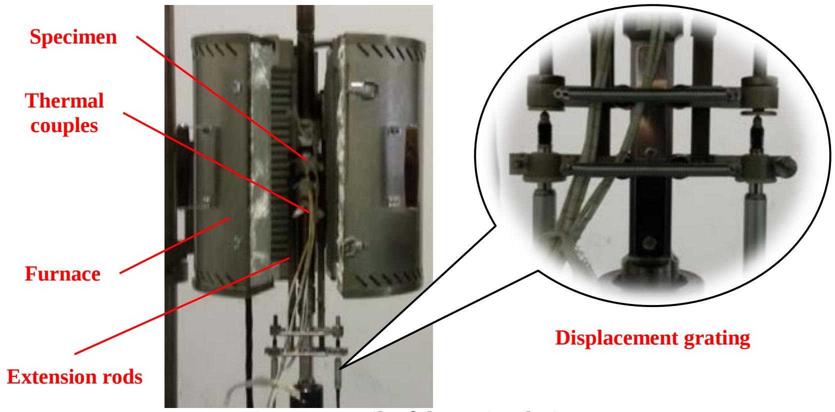

Figure 3. Details of the testing devices

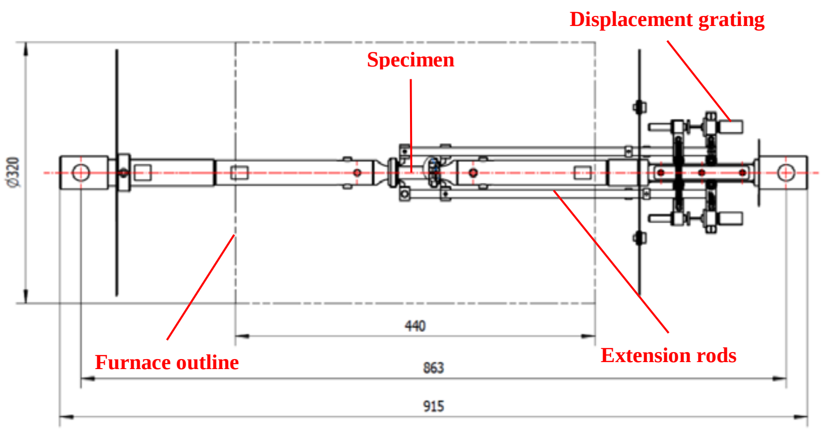

Figure 4. High temperature extensometer system

High temperature extensometer system, shown in Figure 3, creates a 50mm gauge which could collect more displacement data between the gauge scope before the coupon fail and guarantee that the fractures occur within the gauge. Three thermal couples, connected with temperature control system, binding in a range of 150mm separately on upper rod, surface of specimen and lower rod. Thus, a uniform temperature zone will be generated when the temperature of three thermal couples remain stable.

Steady state test method has been used in these tests. First, the specimen was heated up to a pre-selected temperature at a rate of 20°C/min. During the heating process, free thermal expansion was allowed by keeping zero tensile load. The temperature levels in this investigation basically were 20°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C and 700°C. Then the load was applied by controlling the displacement of the electronic tensile grip until failure while maintaining the set temperature. The strain rate was set to 0.00007/s as the minimum rate specified by ISO 6892-2. Moreover, the sampling frequency was 10 Hz. Most of the experiments were repeated twice for double checking.

Results and discussion

Failure modes

Figure 5~Figure 7 present the failure modes of the all the tested coupons. The caliper read 50mm in every picture as a measuring scale. For GR340 and GR410 steels, visually noticeable elongation and necking of the specimens is occurred at 300°C and higher temperatures. For G550 steels, significant elongation and necking could not be observed until temperature reaches 600°C. All coupons fractured within the gauge scope as wished prior to tests, which means the stress-strain curves recorded from test data acquisition system are real stress-strain relationships along the gauge length. Specifically, GR340 and GR410 steels presented a blue brittle phenomenon around 300°C, evidenced by the dark blue colored oxidation film on the fracture section of specimens, and Figure 8 shows the fracture details.

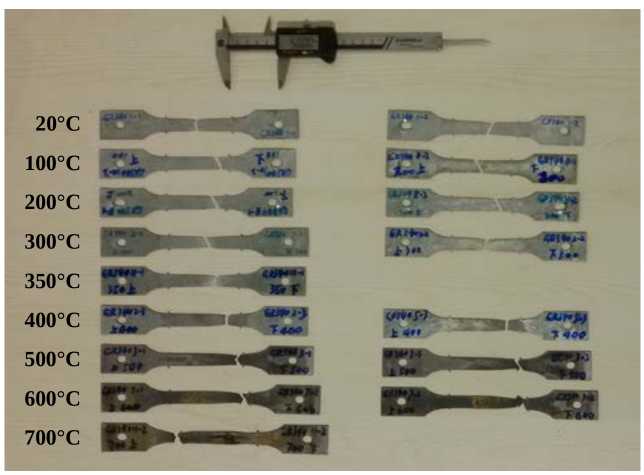

Figure 5. Failure modes for GR340 steel plates

Figure 6. Failure modes for GR410 steel plates

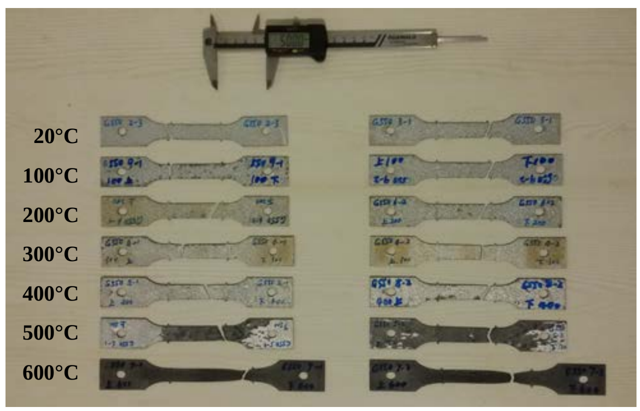

Figure 7. Failure modes for G550 steel plates

Figure 8. Blue brittle phenomenon for GR340 and GR410 steel plates

Stress-strain curves

Since the measurement range of the displacement grating is 12.5mm, the stress-strain curves are given within the strain of 0.2, as shown in Figure 9~Figure 11.

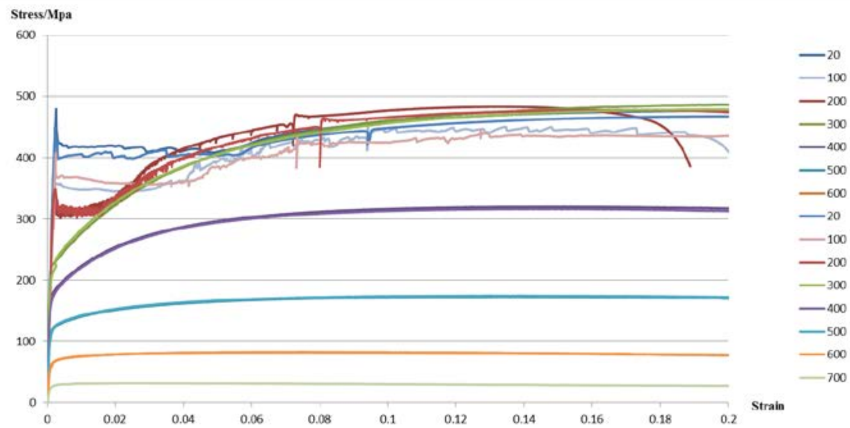

Figure 9. Stress-strain curves of GR340 steels at different temperatures

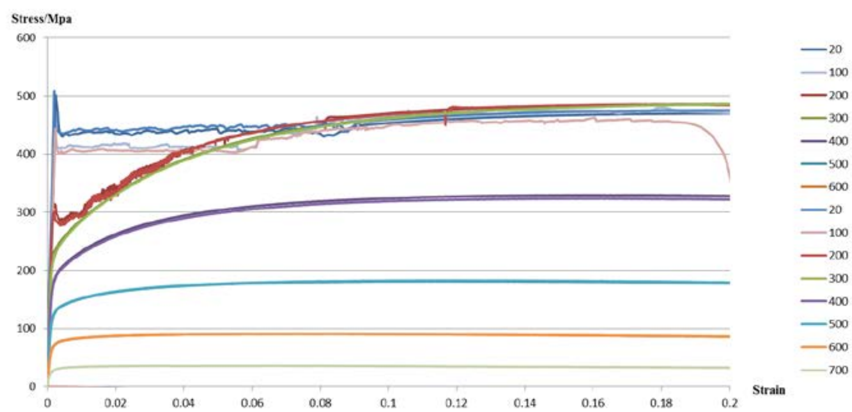

Figure 10. Stress-strain curves of GR410 steels at different temperatures

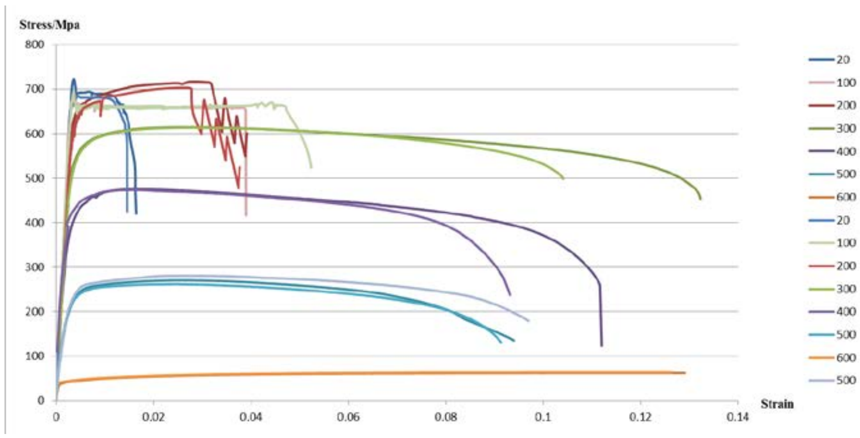

Figure 11. Stress-strain curves of G550 steels at different temperatures

As shown in Figure 9 and Figure 10, the stress-strain curves of GR340 and GR410 steels present similar variation trend: 1) For temperatures below 200°C, an obvious yield plateau occurs when the load reaches the ultimate strength, and disappears after temperatures beyond 200°C. 2) From 20~300°C, the strain-hardening ranges at different temperatures pinch into a small zone, which illustrates that only yield strength experiences degradation at those temperature cases but ultimate strength dose not. 3) At temperatures beyond 200°C the stress-strain curves were of the gradual yielding type, and both yield strength and ultimate strength deteriorate with temperature rising.

Unlike the previous two grade steels, the high strength steel (G550) gave gradual yielding type stress-strain curves at both ambient and elevated temperatures, referring to Figure 11. Then, it appears that the yield strengths do not decrease much up to 200°C. Furthermore, the stress-strain curves have a similar shape and ultimate deformation at temperatures from 300°C to 500°C. When temperature reaches 600°C, the ultimate strain increases significantly. Meanwhile, the load decreases very slowly after the ultimate strength at this condition, and the corresponding failure mode changes to ductile fracture with clear necking.

Retention factors

Primarily, Table 1 shows the tensile test results of all three steels at ambient temperature, which are fundamental parameters for calculating high temperature material properties. Besides the apparent higher strength of G550 steels, the elastic modulus of this high strength steel is also higher than that of GR340 and GR410 steels at room temperature.

Retention factors for the elastic modulus, yield strength and ultimate strength were computed as the ratios of material properties at high temperatures to their values at ambient conditions which is 20°C in this paper. The elastic modulus was calculated by fitting the initial portion of the stress-strain curves via using the least squares method, following ISO 6892-2. For the curves with smooth and long yield plataeu, the yield strength was taken as the average value of stresses in the plataeu. Then for the gradual yielding cases, the yield strength was determined by the 0.2% proof stress method, which uses the intersection point of the stress-strain curve and the proportional line offset by 0.2% strain. Results are shown in Table 2.

Table 1. Mechanical properties of cold-formed steel plates at ambient temperature

Steel Grade	E_{20}(Gpa)	$Fy_{0.2,20}$(Mpa)	$F_{u,20}$(Mpa)
GR340	211.9	411.3	472.2
GR410	212.9	434.6	488.1
G550	218.5	686.8	689.8

Table 2. Retention factors for the elastic modulus, yield strength and ultimate strength

	GR340, t = 0.96 mm			**GR410, t = 0.96 mm**			**G550, t = 1.16 mm**		
T(°C)	$\frac{E_T}{E_{20}}$	$\frac{F_{y0.2,T}}{F_{y0.2,20}}$	$\frac{F_{u,T}}{F_{u,20}}$	$\frac{E_T}{E_{20}}$	$\frac{F_{y0.2,T}}{F_{y0.2,20}}$	$\frac{F_{u,T}}{F_{u,20}}$	$\frac{E_T}{E_{20}}$	$\frac{F_{y0.2,T}}{F_{y0.2,20}}$	$\frac{F_{u,T}}{F_{u,20}}$
20	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
100	0.9375	0.8697	0.9492	0.9413	0.9365	0.9659	1.0262	0.9593	0.9712
200	0.9674	0.7869	1.0516	0.9672	0.6770	1.0044	0.9756	0.9774	1.0572
300	1.0755	0.5932	1.0540	1.0556	0.5725	1.0414	0.9132	0.8358	0.9142
400	0.8914	0.4666	0.6802	0.7846	0.4674	0.6888	0.6099	0.6649	0.7066
500	0.6024	0.2138	0.3807	0.5777	0.2130	0.3844	0.4657	0.3569	0.3964
600	0.2872	0.1761	0.1809	0.3139	0.1822	0.1924	0.2534	0.0652	0.0941
700	0.1590	0.0698	0.0675	0.1672	0.0700	0.0743			

Ductility

In this study, the final gauge length after fracture for cooled down specimens were measured by piecing the segments of specimens tightly on fractures. Afterwards, percentage elongation after fracture, calculated from original and final gauge length, was used to indicate the ductility of steel plates. Table 3 gives the average percentage elongation after fracture at different temperatures for three types of steels and its normalized value is shown in Figure 12.

Table 3. Average percentage elongation after fracture (cooling down) at different temperatures

T(°C)	Percentage elongation after fracture $A_T = \frac{l_{u,T} - l_0}{l_0} \times 100$ (%)

	GR340	GR410	G550
20	32.02	29.99	2.76
100	22.71	20.82	6.06
200	22.40	23.92	3.94
300	40.25	41.41	12.01
400	43.18	45.67	10.34
500	49.07	54.17	10.68
600	63.80	66.97	68.38
700	64.00	56.80	

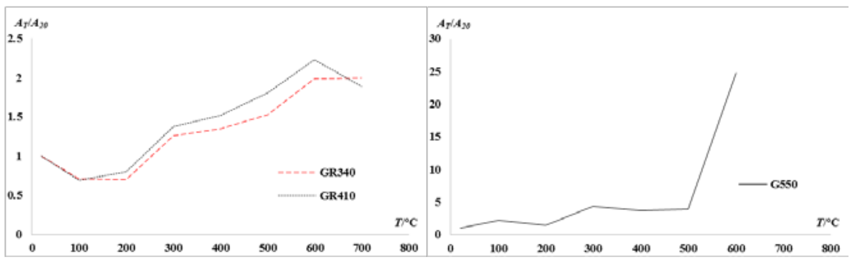

Figure 12. Normalized average percentage elongation after fracture at different temperatures

It is interesting to note that the ductility of GR340 and GR410 steels, from 20°C to 200°C, decreases with increasing temperature. This material behavior may be attributed to chemical transformations taking place in the steel base. After 300°C, the ductility grow continually for chemical change having been taken over by temperature as the dominate factor.

High strength steel (G550) shows lower ductility than that of middle strength steel (GR340 and GR410) at ambient temperature due to the different treatments in manufacturing process. Before 200°C, the ductility of G550 steels maintain low values and even close to room temperature value. Then there was a higher platform of ductility in the range 300°C~500°C, which was still lower than that of middle strength steel at same temperatures. Up to 600°C, effect of strain hardening and heat treatment has been eliminated so that three different steels perform a same level of ductility.

Comparison of reduction factors with those provisioned in design codes and available research results

Figure 13~Figure 16 provide the retention factors for CFS plates obtained through steady-state tests from this study, current design codes and other publications available in the literature.

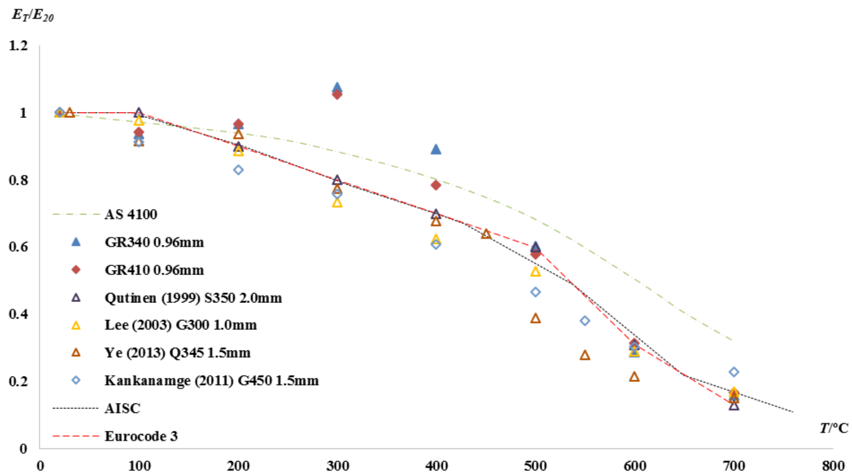

Figure 13. Comparison of the retention factors of elastic modulus for GR340 and GR410 steels according to test results with the current design rules and available research results.

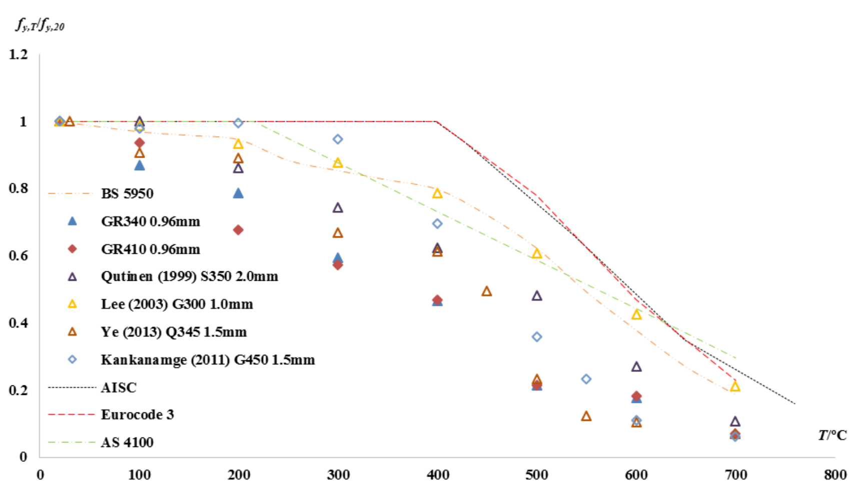

Figure 14. Comparison of the retention factors of yield strength for GR340 and GR410 steels according to test results with the current design rules and available research results.

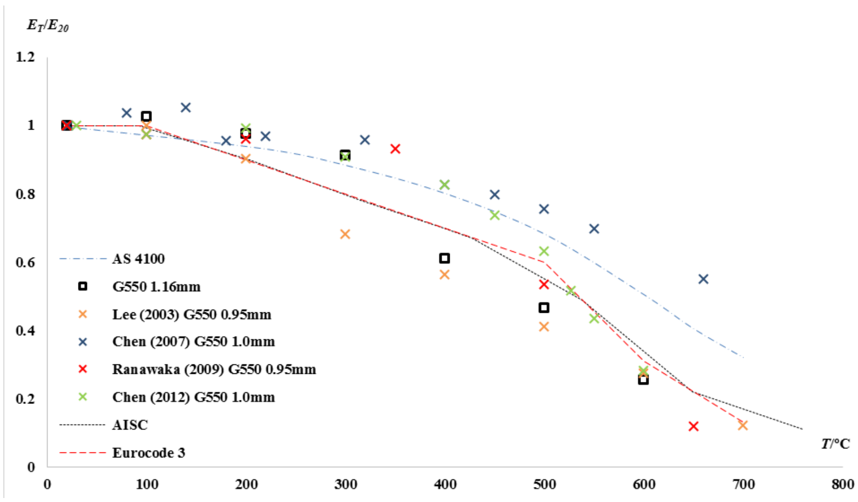

Figure 15. Comparison of the retention factors of elastic modulus for G550 steels according to test results with the current design rules and available research results.

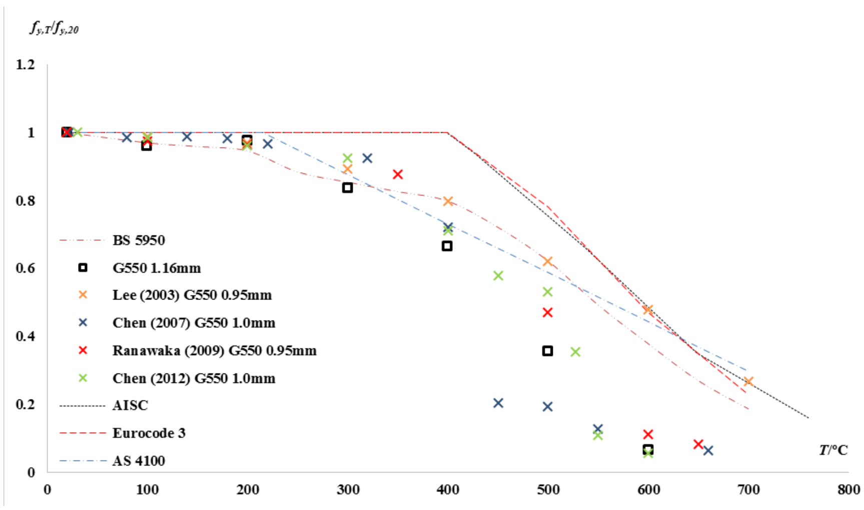

Figure 16. Comparison of the retention factors of yield strength for G550 steels according to test results with the current design rules and available research results.

Those scatter diagrams show that a significant dispersion in existed data on the retention factors of elastic modulus and yield strength which can be mainly attributed to the measuring method, strain rate, heating rate, material type, and the criteria used to determine the parameters. However, it is still meaningful to produce statistical conclusion for reduction of material properties on CFS at elevated temperatures.

By comparing tests data in this paper and other research efforts for CFS sheet with current design codes, retention factors from existing steel design codes are generally unsafe, especially for yield strength prediction. Yield strength retentions factors from hot-rolled steel experimental data provisioned by AISC and Eurocode 3 were the most unconservative, whereas AS 4100 and BS5950 are less unconservative relatively. This confirms that by direct using retention factors developed for hot-rolled steel to calculate yield strength are not suitable for CFS. As for elastic modulus, retentions factors predicted by Eurocode 3 and AISC agree well with the present middle strength steels tests data before 500°C, but somewhat unconservative beyond 500°C. These two curves are also suitable for G550 steels, although a little conservative around 300°C. In addition, the elastic modulus retentions factors curve provided by AS 4100 are unconservative beyond 400°C for both middle and high strength steels.

Therefore, the provisioned curves in current codes cannot be used to calculate the retention factors for CFS plates considered in this study. Also, most of the provisioned equations based on past investigations are not suitable for predicting the degradation properties of CFS sheets mentioned in this paper due to significant scatters existence.

Future work

Considering the dispersion of tests data on CFS plates and inapplicability of hot-rolled steel high temperature material models, it is highly important to propose a set of accurate and easy to use prediction constitutive models for CFS sheets at elevated temperatures by means of statistical approaches and numerical calculations.

Conclusions

This paper has reported a detailed experimental study of the material properties of cold-rolled thin-walled steel plates at elevated temperatures. The experimental study included tensile coupon tests conducted on GR340, GR410 and G550 steels via steady state test methods, and a careful discussion of the test results was included. Neither the current design codes nor the proposals by other researchers provided accurate retention factor predictions for both the yield strength and the elastic modulus of cold-formed steel plates considered in this study. At last, further efforts for retention factor prediction equations and constitutive models of CFS plates have been schemed.

Acknowledgements

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Appendix. –Notation

The following symbols are used in this paper:

A_{20}	=	Percentage elongation after fracture at 20°C
A_T	=	Percentage elongation after fracture at T°C
E_{20}	=	Elastic modulus at 20°C
E_T	=	Elastic modulus at T°C
$F_{y0.2,20}$	=	Yield strength at 20°C
$F_{y0.2,T}$	=	Yield strength at T°C
$F_{u,20}$	=	Ultimate strength at 20°C
$F_{u,T}$	=	Ultimate strength at T°C
l_0	=	Original gauge length
$l_{u,T}$	=	Final gauge length at T°C
T	=	Temperature

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